# Moment-Frequency distribution as a constraint for hydro-mechanical modelling in fracture networks

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# MOMENT-FREQUENCY DISTRIBUTION USED AS A CONSTRAINT FOR HYDRO-MECHANICAL MODELLING IN FRACTURE NETWORKS

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Shear re-activation of deep fractured rocks for EGS purposes is accompanied by microseismicity. From our numerical hydro-mechanical coupling in discrete fracture network models which incorporates stress drops with known amplitudes and neglects the influence of static stress changes, it happens that the moments of induced seismic events are scaling with the power 3 of the fracture size. It follows that the value of the slope of the moment-frequency diagram better known as the b′ value obtained from numerical experiments correlates with the exponent of the power law distribution used for the fracture size generation. Our suggestion is therefore to use these diagrams for constraining the fracture network generation process.

## 1. INTRODUCTION

Concepts for recovering energy from deep hot crystalline rocks have gradually evolved as the data base was increased by experiences from several Hot Dry Rock projects during the last 30 years. The early vision[1)] promoted at the Los Alamos National Laboratory of taping into an inexhaustible and widely available energy using the so called man-made-geothermal-system based on the creation of parallel hydraulic fractures linking a pair of wells in homogeneous impermeable rock had to be abandoned, and the technology was adapted to the geological conditions underground. The concept forward to create a reservoir has therefore been the acceptance of the view that the interconnection of boreholes over inter-well distances of commercial interest occurs through the pre-existing volumetric network of fractures, faults and joints of hydraulic significance. Hydraulic experiments at high over pressure and elevated flow rates performed into these pre-existing conductive structures resulted in a shearing and self propping process better known as ‘stimulation experiments’, a term therefore preferred to ‘hydraulic fracturing’ experiments. This way of thinking the development of a reservoir was first applied in the Camborne School of Mines project run at Rosemanowes, Cornwall[2)], then at Hijori site (Japan) and again in a graben extensional setting at the Soultz sous Forêts site, in France, where valuable results with regard to scientific and pre-industrial objectives have been obtained at a depth of around 3.5 km. After this significant success at moderated depth, the Soultz project has evolved toward a three well system at a depth of 5 km[3)], and a temperature close to 200°C, with the aim of prefiguring a pilot plant of some 50 to 75 MW of thermal power. Similar production objectives are assigned to the most recent projects that started at Cooper basin, in Australia) and Bâle in Switzerland.

## 2. MECHANISM FOR INDUCED MICRO SEISIMICITY IN EGS ACTIVITY

### (1) A variety of in situ observations

As an HDR reservoir is being formed following the stimulation strategy, fracture walls and rock blocks are moved very slightly by the pressure of the injected fluid. Shear stresses are partly liberated and the resulting small sliding movements give rise to low frequency stress waves similar to, but much smaller than those caused by earthquakes. Microseismic technology has been developed from the early days to identify these signals and locate their points of origin (See fig.1). A major goal of monitoring the induced seismicity is to obtain information[4)] about the pattern, the size and orientation of ruptured fractures away from the wells given the assumption that these pressurized and damaged zones will further act as preferential flow paths.

However, as experiences were cumulated at Soultz and other places, a new puzzling set of questions surges, dealing with micro seismic events with moment-magnitude M in the range of 2 to 3.These largest events tend to occur after injection ceases (fig. 2) and therefore are nearly out of control. Such small earthquakes can however be felt and could alter the public acceptance to HDR project in urban areas.

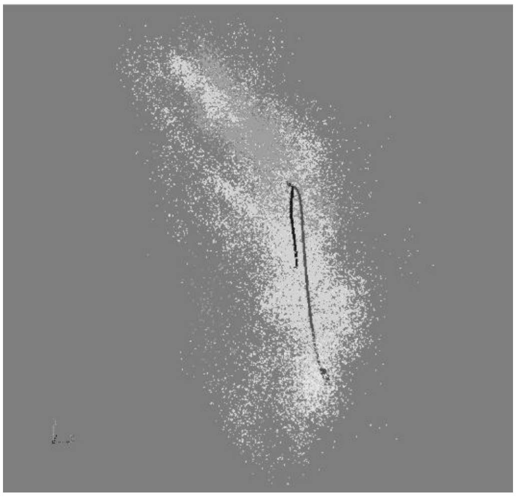

**Fig.1**: Plan view of the locations of the generated events at Soultz after the hydraulic stimulation of GPK2 borehole (top trace), GPK3 borehole, and GPK4 borehole (bottom trace)

Although these events are clearly resulting from the operator's activity, their mechanisms remain poorly understood and the question of their prediction in time and space to manage the risks without exceeding tolerable thresholds is matter of debates[5].

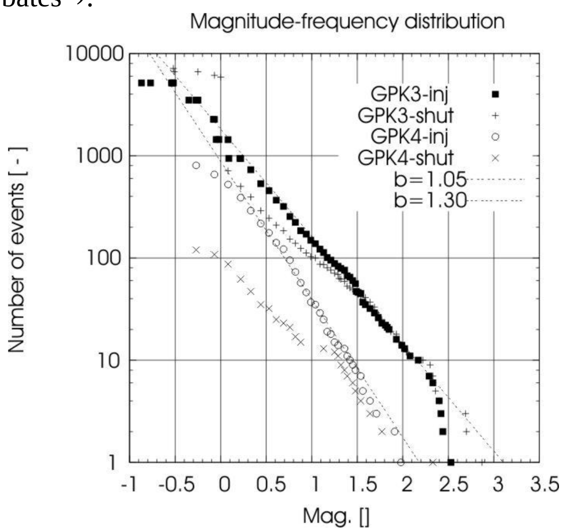


**Fig.2**: Log-log plot magnitude-frequency distributions of events recorded during and after the stimulations of GPK3 (2003 experiments) and GPK4 (2004 experiments) boreholes.

Interestingly, this problem of seismic hazard did not rise in the early and shallower UK project, most probably because of the local low variability in the joint size distribution. Measured magnitudes were very moderated, stress drops lower than 0.1 MPa, and the b′ slope coefficient is about 1 (Fig.3).

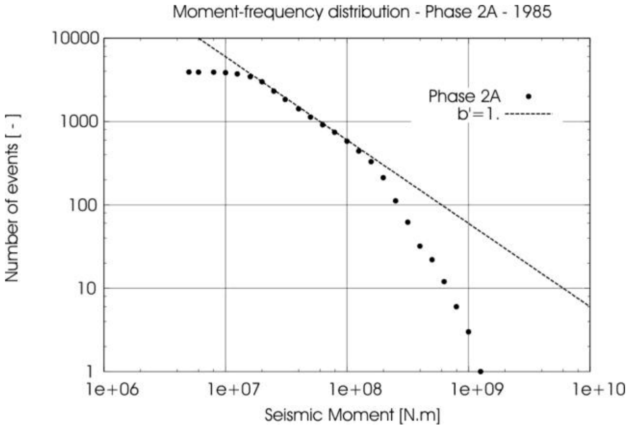


**Fig.3**: After ref [2]. Distribution of seismic moments at Rosemanowes, phase 2A, UK project, reprocessed from figure 4.9*, chap. 4.1.4, Source Inference*

## (2) Toward a quantitative understanding of the hydro-mechanical processes

Various attempts have been proposed to incorporate micro-seismicity in modeling work and some 3D numerical tools have been gradually developed to account for this new but sparse structural data. A review of codes specific to HDR research is given in[7], but very few of them are dedicated to the understanding of reservoir development and to the transient analysis of shear growth during fluid injections, with estimates of the seismic moments. The FRIP[8] package developed in the frame work of the CSM project belongs to this set of very first modeling tools and took advantage of the rectangular blocky pattern of the investigated rock mass. As a result shear could propagate, with fluid pressure, without any large rupture generation. Owing to the more general random nature of the fracture population in deep hard rock masses, discrete fracture networks approaches have been promoted[9] in 3 dimensions with hydro-mechanical coupling capabilities to describe the propagation of the shearing process in a random fracture network, in response to a fluid pressure perturbation at a well. Using the FRACAS code[10] to some data recorded in 2004 during GPK4 borehole stimulation at Soultz sous Forêts, we showed that the occurrence of late events is predictable due to the low local hydraulic diffusivity. At the edge of the reservoir, depending on far field permeability, fluid pressure can go on increasing during day-long periods, and events, small or large, can be triggered as they were during the injection period.

## 3. DISCUSSION ON THE FRACTURE SIZE DISTRIBUTION

Following the above discussion, we are now looking at the possibility of deriving some additional knowledge from the analysis of the temporal and spatial spreading of the shear failure mechanism. A seismic moment $M$ can be evaluated at any time when a displacement consequent upon a shear rupture is calculated in the model, according to $M=G.S.u$, $G$ being the shear modulus, $S$ the area of the sheared zone and $u$ the displacement. From our numerical hydro-mechanical coupling which incorporates stress drops with known amplitudes and neglects the influence of static stress changes, it happens that seismic moments are scaling with the power 3 of the fracture size, since the area $S$ and displacement $u$ are a quadratic and linear functions of fracture size.

As it is common for fracture size description in hard rocks, we use a power law distribution. The value of the slope of the moment frequency diagram better known as $b'$ value obtained from numerical expe -riments should correlate with the exponent $a$ of this power law. The relation should be $a = 3.b'$. A direct outcome of this finding is that site specific seismic moment-frequency diagrams or magnitude -frequency diagrams might be directly usable as a constraint for fracture network generation, provided a scaling relationship between both measures like the one by[11] can be established for small events.

At Rosemanowes site (Fig.3), $b'$ coefficient is close or larger to 1. This corresponds to a power law exponent $a \geq 3$ for the fracture size distribution. This behaviour would correspond to fracture networks where hydraulic properties are controlled by the fracture density (percolation theory) and not by the occurrence of large fractures. This fits with the average size of the joints estimated[2] at this site in the order of 10 to 25 m. As some seismic magnitudes have been made available (Fig.2) for the Soultz site, we will address this question of the size of the ruptured fractures using the FRACAS code upon a series of synthetic numerical networks.

## 4. NUMERICAL EXPERIMENTS

Networks are constructed as in [10], with the aim of having comparable hydraulic diffusive properties, as characterized by [12]. This is obtained by adjusting fracture density and fracture size so the $d_{32}$ index (fracture area/unit rock volume) ratio is similar from one network to an other. A value of 0.038 $m^2/m^3$ was obtained for GPK4 area. Fig.4 shows two cross sections of admissible networks. A same diffusivity (Fig.5), close to 0.15 $m^2/s$, can be obtained for two sets of 10 equiprobable networks. The shearing process that develops during the four days long injection tests simulated in the series of 3D fracture networks can also be illustrated by the distribution of seismic moments. A linear trend can be identified, on fig.6, with a $b'$ slope value, clearly related to the corresponding $a$ value.

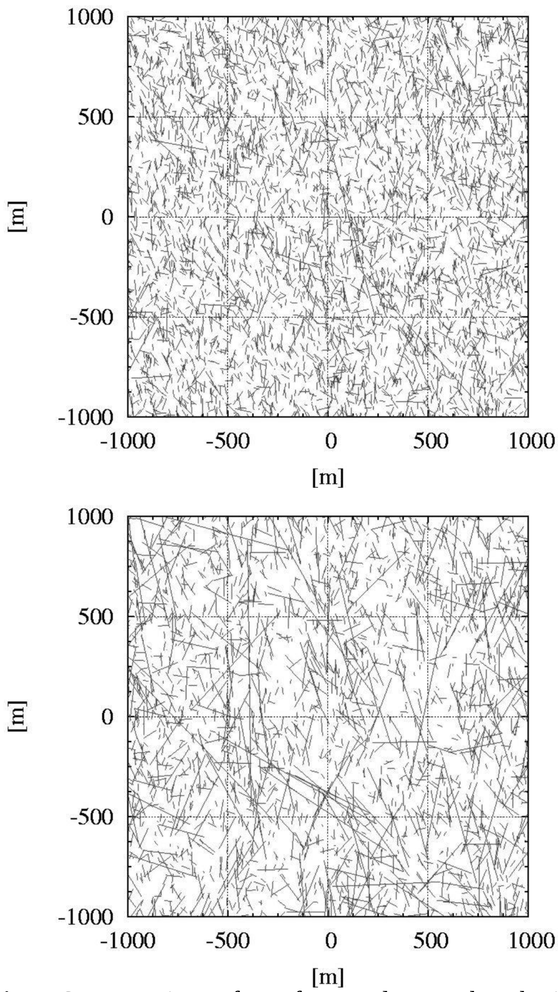


**Fig.4**: Cross sections of two fractured networks, obtained with different density and size distribution parameters, but exhibit the same overall hydraulic diffusivity; Top $a=3.5$, bottom $a=2.1$

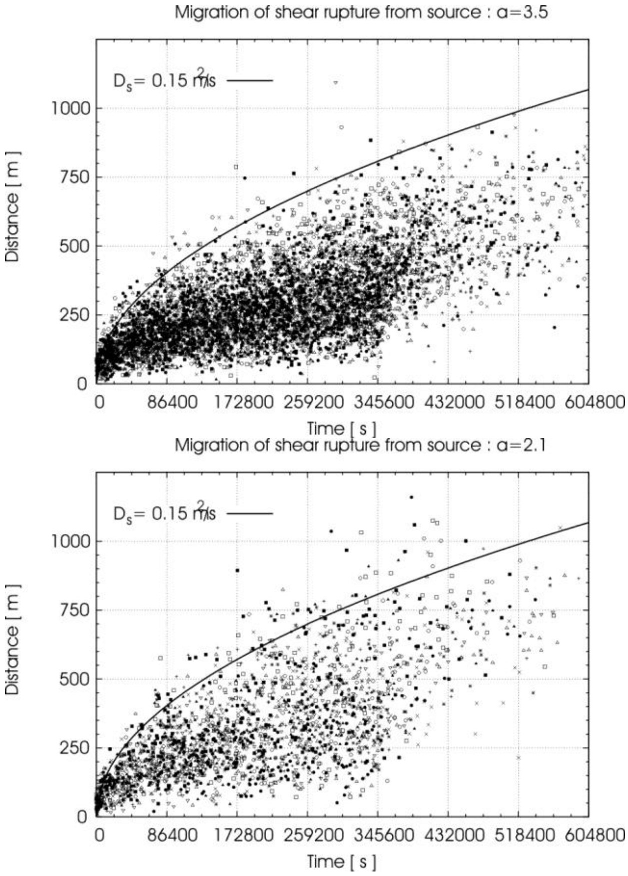


**Fig.5**: Sheared events reported in a time/distance to source diagram, for ten equiprobable realisations of the networks. Top `a=3.5`, bottom `a=2.1`

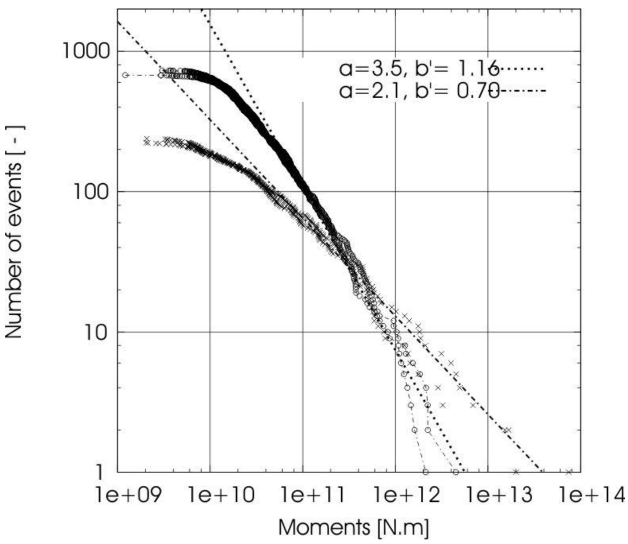


**Fig.6**: Seismic moment frequencies reported in a log-log plot for two of ten network realisations, with respectively `a=3.5` and `a=2.1`

## 5. RESULTS AND PERSPECTIVES

Comparing Fig 6 and the data recorded in Fig 2 would suggest, using [11], that an appropriate b-value is `b~1.15`, and hence `b'~0.85`. This gives `a` in the range of `2.1` and `2.7`. Such a value, lower than 3, corresponds to networks where flow is partly controlled by the large fractures (multipath scheme). Most probably the network is not of block type. This `a` value could also indicate a possible limit for a potential large scale seismic event.

Progress could be gained, debating on the shear strength parameter. In the present approach no stress is induced when a fracture-cell fails. But thinking to a slip-stick process with a stress accumulation on the remaining contact is now possible in our DFN model, using Discontinuity Displacements nume -rical techniques. Fracture shear strength could be distributed on the cells that mesh the large fractures, with a broad bandwidth. Gradual rupture at the cell scale with calculations of stress redistribution at the fracture scale might allow the rupture criteria to be met at the more resistive places of the fracture. The dislocation of the entire fracture would be the final step of the rupturing process, with a larger stress drop and therefore a potentially large magnitude.

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